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(c) Nuclear Spin Thermometry and Relaxation Below 1°K,*

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The need for a new technique which provides clear measurements of thermodynamic temperatures below 1°K has been motivated by the nuclear cooling experiments on copper of Kurti and his collaborators.[1] The limited temperature range of applicability and the laborious calibration procedures associated with temperature measurements in terms of electrical resistance or the paramagnetism of magnetically cooled salts are well known. Kurti and his collaborators have demonstrated, by mutual inductance methods, that nuclear spin susceptibilities in the 10^{-5}-10^{-6} °K spin-temperature range can be measured. Above this temperature range, however, there is insufficient sensitivity for practical measurement by their method. Because the total susceptibility is measured, there exists also the possibility that electronic paramagnetic impurities may contribute to the measurements. A pulsed nuclear free-precession type of experiment is reported here, which avoids the above limitations by measuring directly the nuclear magnetism due to known nuclear spins, at thermal equilibrium among themselves, in various metals over a wide range of spin temperatures. The nuclear

spins in metals may or may not be in thermal equilibrium with the electrons, which serve as the important lattice degrees of freedom at very low temperatures. Measurements of nuclear signal amplitudes proportional to the nuclear magnetization M_z, and spin-lattice relaxation times T_1, permit separate measurements respectively of the nuclear spin temperature T_n and the electron or lattice temperature T_ℓ.

Following the process of adiabatic demagnetization, a sample of many metallic wires (~1/20 mm diameter wire size) embedded in a paramagnetic salt acquires an equilibrium temperature of the order of $0.01^{\circ}K$ in our experiments. The pulse technique injects a controlled minimum of heat into the system by the use of small magnetic fields, so that the sample is not warmed appreciably above the temperatures achieved by demagnetization.

Essentials of the pulse method[2] are indicated in Fig. 1. A small magnetic field H_o provides a z axis about which free precession of $\underset{\sim}{M}$ takes place at frequency $\omega = \gamma H_o$, where γ is the gyromagnetic ratio. At $t = 0$ a half sine wave of magnetic field $H_1(t)$ along the y axis is turned on by initiating the discharge of a capacitance through an inductive coil oriented along the y axis. Assuming for simplicity that $H_1(t)$ is a constant field in the short pulse time interval $0 \leq t \leq t_w$, let $\underset{\sim}{M}$ precess about the $\underset{\sim}{H}_o + \underset{\sim}{H}_1$ field for a time $t_w = \pi/(\gamma \sqrt{H_o^2 + H_1^2})$. At $t = t_w$ the maximum component of magnetization $M_{xy} = M_z \sin 2\theta$ appears in the xy plane, where $\theta = \tan^{-1}(H_1/H_o)$. For $t \geq t_w$, M_{xy} precesses freely about H_o, and decays roughly in a time T_2 determined by spin-spin interactions (see Fig. 2). The

nuclear signal due to M_{xy} is induced along the x axis in an untuned receiver coil consisting of 700 turns of number 40 manganin wire, which is connected to a wide-band amplifier.

Although the largest signal is obtained for $H_1 = H_o$, it is desirable to let $H_1 \ll H_o$ and tip M_z through a small angle θ. It is then possible to measure signal amplitudes following successive pulses in one cooling experiment, and therefore measure T_1. Also overheating of the wire sample is avoided by minimizing induced eddy currents.

At the temperature of 1°K, where $T_n = T_\ell$, and T_ℓ is measured by conventional methods, the nuclear signal $M_{xy} \propto 1/T_n$ can be calibrated and referred to M_{xy} signals which measure temperatures T_n less than 1°K. The average of the relaxation times of $Cu^{63,65}$ spins in the T_ℓ temperature range of 0.02°K to 1.0°K obeys the Korringa law[3] $T_1T_\ell = 1.12$°K sec. This conforms with the result found by Kurti and Hobden,[4] that the electron temperature T_ℓ does not follow T_n upon achieving $T_n < T_\ell$ following a second stage of nuclear demagnetization. Relaxation measurements in Na^{23} metal (Fig. 3) at $T_\ell \approx 0.02$°K give $T_1T_\ell = 4.5$°K sec at high fields, in agreement with the data of Anderson and Redfield.[5] However, the dependence of T_1T_ℓ for sodium at lower fields is not in agreement with their results at 1.1°K, while the same data for copper does agree. The sodium metal, dispersed in oil, was successfully cooled by contact with a bundle of copper wires which is maintained at 0.02°K by the paramagnetic salt. Measurements of platinum signals (Pt^{195}) from the wire bundle in the vicinity of $T_\ell = 0.02$°K gives $T_1T_\ell = 6.9 \times 10^{-2}$ °K sec, which contrasts with values of

1.64×10^{-2} °K sec (at $T_\ell = 78$°K) and 2.25×10^{-2} °K sec (at $T_\ell = 300$°K) measured by Rowland[6] using the saturation resonance method. Relaxation measurements on platinum, sodium, and other metals are being continued, including also measurements of the Knight shift.

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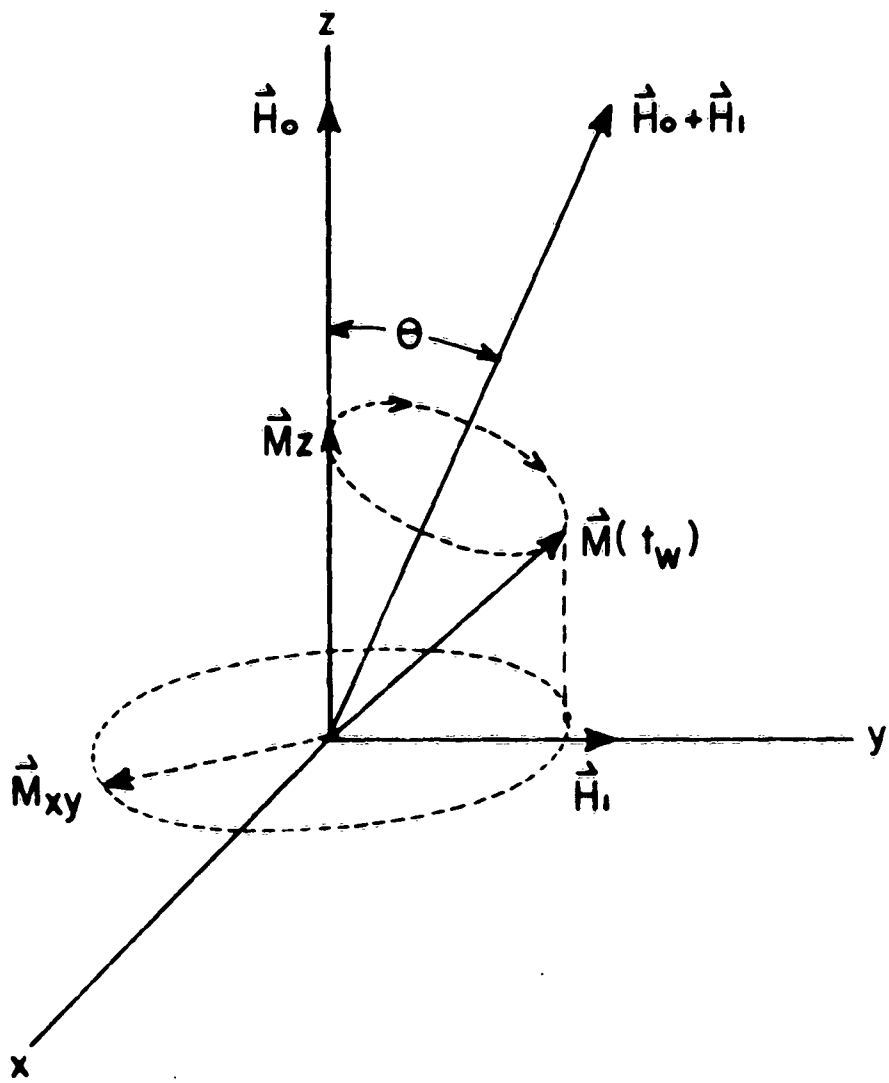
FIGURE LEGENDS

Fig. 1. Precession of magnetization, $\underset{\sim}{M}$, about resultant field $\underset{\sim}{H}_o + \underset{\sim}{H}_1$, producing an M_{xy} component in the xy plane.

Fig. 2. Oscilloscope trace, showing free induction decay oscillations of Na^{23} metal powder in $H_o \cong 22$ gauss, with $T_\ell \cong .02^\circ K$ and total time of trace $\cong 900$ μsec. Clearly demonstrated is a field-independent beat structure due to dipolar interactions among the Na nuclei.

Fig. 3. Curves showing nuclear spin temperature T_n as a function of time after nuclear demagnetization of Na^{23} from initial field and temperature of 6000 gauss and $.02^\circ K$ respectively. T_1's are computed from the slopes of these curves.


z
$\vec{H}_o$
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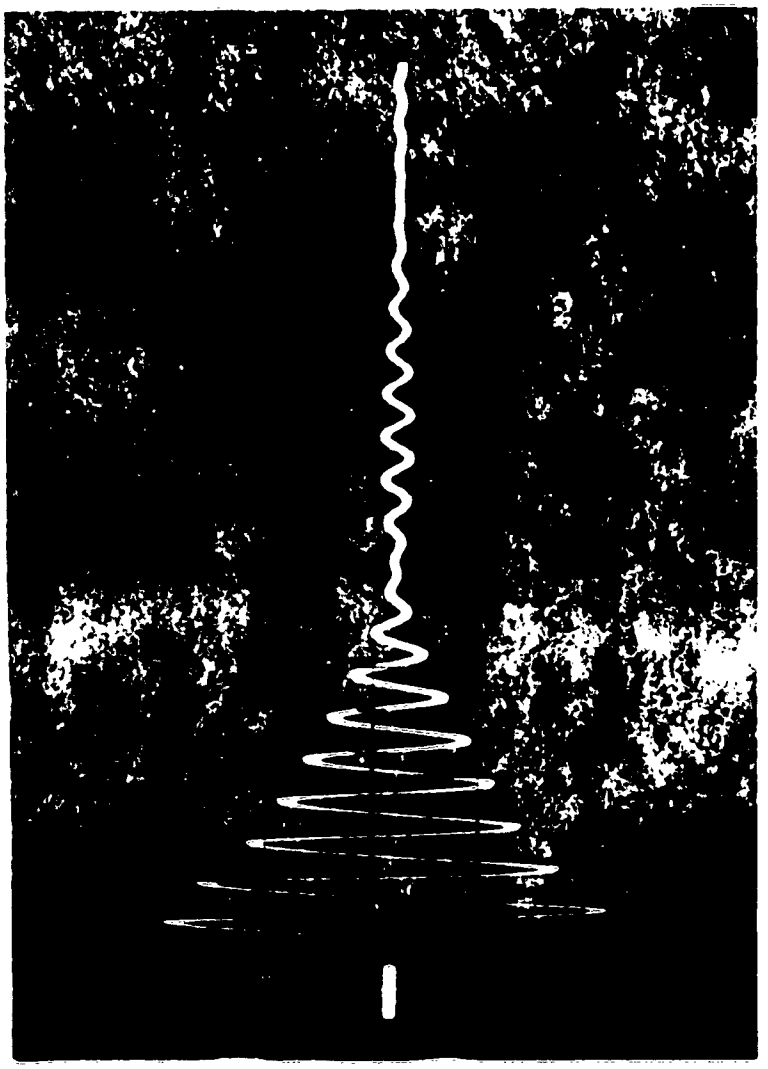

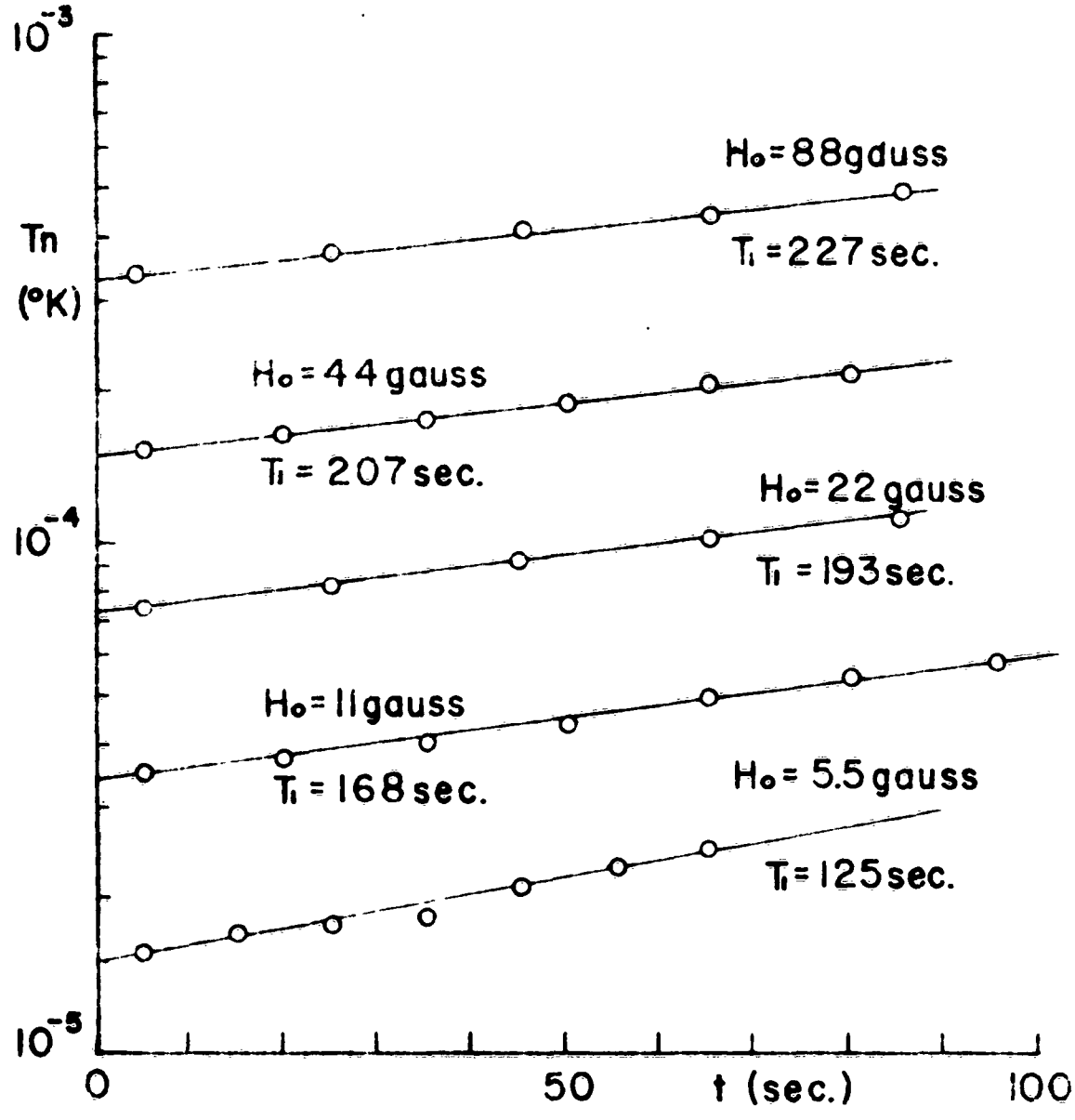

NUCLEAR COOLING OF Na